Quantitative Ultrashort Echo Time Magnetic Resonance Imaging Evaluation of Postoperative Menisci: a Pilot Study

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Abstract *Background:* Magnetic resonance imaging (MRI) visualization of meniscal signal is particularly challenging as the highly organized ultrastructure of meniscal fibrocartilage yields very short T2 values (~6 ms) and a paucity of signal intensity during conventional image acquisition. *Question/Purpose:* The purpose of this study was to evaluate the feasibility of imaging postoperative menisci using an experimental, quantitative ultrashort echo time (UTE) MRI pulse sequence. This sequence acquires short echo images (echo time (TE) ~0.3 ms) to produce multi-echo images for quantitative T2* calculations that provide an objective measure of collagen organization. *Patients and Methods:* MRI scans of the knee were acquired at 6- and 12-month intervals on a clinical 3.0 T scanner following meniscal surgery in eight patients (ages 13–41), four of whom underwent repair and the other four partial meniscectomy. Conventional MRI sequences were qualitatively evaluated for meniscal morphology and signal and

correlated with quantitative UTE results. *Results:* A wide range of mean T2* values for both postsurgical groups was measured, and these values changed for each patient between the 6- and 12-month intervals. In many instances, the UTE sequence demonstrated quantitative differences between the two time intervals that were not detected with conventional sequences. *Conclusions:* This pilot study presents preliminary, observational data to be used as a baseline for future studies. Although the T2* values did not reveal a trend in either group or correlate with expected signal changes on conventional MRI, we speculate that the UTE sequence may detect ultrastructural alterations in meniscal composition that are otherwise not perceived with routine fast spin echo (FSE) sequences.

Keywords magnetic resonance imaging · quantitative · ultrashort TE · meniscus

Introduction

Evaluation of the postoperative meniscus, following partial meniscectomy or repair, can be challenging. Current methods to analyze meniscal healing include clinical assessment, magnetic resonance imaging (MRI), computed tomography, and MR arthrography and second-look arthroscopy [3, 5]. Clinical assessment typically includes patient history and physical examination and is quite subjective [4]. Although second-look arthroscopy is considered the standard for determining meniscal healing following surgery [3], it is an invasive procedure and does not permit direct visualization of the substance of the meniscus beneath the articular surface. MR imaging is a non-invasive modality and is best suited for the routine evaluation of meniscal integrity preoperatively and postoperatively.

Conventional MRI findings that suggest incomplete meniscal healing or new tear include the following: linear intrameniscal fluid-intensity signal extending to an articular surface on intermediate-weighted images, abnormal meniscal morphology inconsistent with that of a

Level of Evidence: Type III. This is a prospective, observational cohort (longitudinal) study.

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postoperative meniscus, such as a displaced flap, or a tear at a location remote from the surgical site [1, 9]. The presence of linear intrameniscal fluid-intensity signal extending to an articular surface is the most important MRI finding in diagnosing a non-healed or recurrent tear of the postoperative meniscus.

In a previous study assessing regional healing rates of repaired meniscal tears using double-contrast knee arthrography as the standard, van Trommel et al. evaluated the extent of intrameniscal signal at the site of repair and concluded that if the signal reached both articular surfaces, this denoted non-healing whereas if the signal approached only one articular surface, the repair was partially healed [8].

MRI visualization of meniscal signal, however, is particularly challenging as the highly organized ultrastructure of meniscal fibrocartilage yields very short T2 values (~6 ms) and a paucity of signal intensity during routine image acquisition. Quantitative MRI (qMRI), with its ability to quantify tissue relaxation times, presents an objective measure of collagen organization. Current qMRI techniques such as T2* mapping for articular cartilage cannot capture the very short T2 values of meniscal fibrocartilage [10]. T2* mapping using an ultrashort echo time (UTE) pulse sequence acquires short echo images (echo time (TE) ~0.3 ms) to produce multi-echo images for quantitative T2* calculation [2].

Our group recently assessed an UTE pulse sequence in an ovine model to detect temporal and zonal differences of meniscal structure and composition [2]. The aims of this pilot study in humans were to determine if there would be a measurable trend in the T2* values of menisci at 6- and 12-month intervals using an UTE pulse sequence following surgery and also to assess if these T2* values correlated with morphological and signal changes of the meniscus on conventional, two-dimensional (2D) proton-density (PD) fast spin echo (FSE) images. We hypothesized that higher T2* values would correspond to increased meniscal signal at the repair site as determined on conventional FSE images, with a disorganized and/or “non-healed” meniscal matrix corresponding to higher T2* values.

Patients and Methods

Following Institutional Review Board (IRB) approval with informed consent, MR images of eight patients (five male, three female, ages 13–41) were acquired at 6- and 12-month intervals following meniscal surgery. Four patients underwent repair and the other four partial meniscectomy.

Two men and two women, ages 13–41, underwent meniscal repair. Patients 1 and 2 had displaced bucket handle tears of their lateral meniscus, and patients 3 and 4 had vertical tears within the vascular zone of the posterior horns of their lateral menisci. The repairs of the bucket handle meniscal tears were augmented with platelet-rich fibrin matrix (PRFM, Cascade® Autologous Platelet System, Musculoskeletal Transplant Foundation), while repairs of the vertical longitudinal tears were not augmented (Table 1). PRFM is a platelet-rich plasma variant whereby a fibrin matrix is formed by activation of the fibrin clotting cascade by addition of CaCl₂ and a second centrifugation step. This process minimizes platelet activation and traps non-activated platelets in the fibrin matrix, allowing sustained release of cytokines. The PRFM was made intraoperatively using 9 mL of peripheral venous blood, collected at the start of the procedure.

Three men and one woman, ages 14–33, underwent partial meniscectomy. These patients all had different tear morphologies, including vertical longitudinal, radial, and bucket handle. The operations were performed by four different orthopedic surgeons (Table 1).

Scanning was performed on a 3.0 T clinical scanner (GE Healthcare, Waukesha, WI) using a transmit/receive eight-channel knee coil (Invivo, Gainesville, FL). Two-dimensional FSE PD scans were acquired in the coronal and sagittal planes to assess the morphologic appearance of the knee and meniscus. Acquisition parameters were as follows: echo time (TE)=24 ms, repetition time (TR)=4,000 ms, echo train length (ETL)=10–14, field of view (FOV)=16×16 cm, acquisition matrix (AM)=512×480–384, receiver bandwidth (RBW)=±62.5 kHz, number of excitations (NEX)=1, slice thickness (ST)=3.5 mm, and slice spacing (SS)=0.0 mm. A short-tau fast inversion recovery (STIR) sequence was obtained in the sagittal plane

Table 1 Patient demographics and tear location, type, and operation

Patient no.	Gender	Age (years) at time of surgery	Knee (right/left)	Tear location (lateral/medial)	Tear type and location within meniscus	Surgical technique
Repair group						
1	Male	30	Right	Lateral	Displaced bucket handle	Augmentation with platelet-rich fibrin matrix
2	Male	41	Left	Lateral	Displaced bucket handle	Augmentation with platelet-rich fibrin matrix
3	Female	29	Left	Lateral	Vertical longitudinal posterior horn—vascular zone	Non-augmented
4	Female	13	Left	Lateral	Vertical longitudinal posterior horn—vascular zone	Non-augmented
Partial meniscectomy group						
5	Male	14	Right	Lateral	Horizontal, body and free edge posterior horn	Resection
6	Male	33	Left	Medial	Displaced bucket handle	Resection
7	Female	16	Left	Lateral	Radial tear, posterior horn	Resection
8	Male	16	Left	Medial	Vertical longitudinal, posterior horn	Resection

with the parameters: TE 14–18 ms, TR 4,000–4,500 ms, inversion time (TI) 170 ms, BW ± 41.7 KHz, FOV=16 $\times$ 16 cm, AM=265 $\times$ 192, NEX=1, and ST=3.5 mm. A multi-slice, multi-echo UTE sequence was acquired sagittally for meniscal T2* calculations: TEs=0.3, 4.8, 9.6, and 14.5 ms; TR=350 ms; flip angle=45°; ST=3 mm; SS=0.6 mm; FOV=16 $\times$ 16 cm; RBW= ± 125 kHz; AM=512 $\times$ 801; and NEX=2. The total imaging time was approximately 35 min per knee. To the best of the authors' knowledge, as UTE is not a commercial product, there is no standardized UTE acquisition protocol across sites. Additional echo images to calculate T2* values may be beneficial for species, such as menisci, with short T2* components but come at the expense of prolonged scan time. Our current UTE pulse sequence only permits a four-echo acquisition and requires just over 8 min of scanning to achieve the desired voxel size and sample coverage, a time frame we believe that is most conducive to clinical translation.

FSE PD and sagittal STIR sequences obtained were evaluated by two radiologists in consensus (DBS and WYL) using a scoring scheme adapted from a method previously applied in evaluating the integrity of meniscal transplants [6]. This three-point scoring scheme, as detailed in Table 2, evaluated the degree of meniscal extrusion, the proportion of increased signal greatest in the surgically repaired portion of the meniscus, the presence of a tear in the non-operated portion of the meniscus, the degree of healing, and degree of synovitis.

UTE image acquisition was used to manually segment regions of interest (ROIs) on anterior and posterior horns of the meniscus for subsequent meniscal T2* calculations. The ROIs were drawn over the slice(s) encompassing the postsurgical site. A non-linear offset calculation method was used to calculate the T2* value of meniscus for each pixel within the ROIs. The signal intensity (SI) of the pixel at different TEs was fitted to the equation: $SI(TE) = M_0 \cdot \exp(-TE/T2^*) + C$, where SI(TE) is the signal intensity at echo time, TE, M_0 is proportional to proton density, T2* is the inherent time constant, and C is a constant proportional to the image noise floor. All quantitative MR analyses were performed using custom written programs (Mathworks, Natick, MA, USA).

deviation of the mean T2* values for the four patients' menisci were 6.9 ± 7.5 and 3.0 ± 2.1 ms for the posterior horn and 4.8 ± 2.0 and 4.8 ± 2.2 ms for the anterior horn, at 6 and 12 months, respectively (Table 3). Patients 1 and 2 who had bucket handle tears demonstrated a decline in the T2* values of their posterior horns between 6- and 12-month intervals, whereas patient 1 had a small decrease in the T2* value for his anterior horn, and patient 2 had a slight increase. Patients 3 and 4, who underwent repair of their posterior horn tears, demonstrated variability in the trend of their T2* values between the 6- and 12-month intervals for both the anterior and posterior horns of their repaired menisci. MRI assessment of the FSE sequences demonstrated interval extrusion between 6 and 12 months of the body segment of the meniscus of patient 3, who originally had a vertical longitudinal tear of his posterior horn, as well as increased, mild synovitis. The signal grade for all patients remained the same (e.g., Fig. 1). Patient 4 demonstrated changes in the signal morphology of the repair site between 6 and 12 months with a repair score=1 at 6 months, indicating partial healing, and a repair score=0 at 12 months, indicating complete healing.

Mean T2* values for the partial meniscectomy group demonstrated a wide range and no apparent trend. The mean and standard deviation of the mean T2* values for the four patients' menisci were 3.7 ± 1.5 and 4.3 ± 3.1 ms for the posterior horn and 4.4 ± 1.9 and 4.1 ± 2.8 ms for the anterior horn, at 6 and 12 months, respectively (Table 4). Patients 5, 6, and 7, who had partial meniscectomy of their native menisci, all demonstrated a decline in T2* values of both their anterior and posterior horns between 6 and 12 months, whereas patient 8 who underwent partial meniscectomy of a previously repaired posterior horn meniscus demonstrated an increase in T2* values between 6 and 12 months for both horns. MRI assessment of the FSE sequences demonstrated a relatively unchanged appearance in the menisci, as well as the degree of synovitis in most patients, except in patient 8 in whom no healing and moderate synovitis (score=2) were seen at the 6-month interval, but complete healing and resolution of synovitis were seen at the 12-month interval (Fig. 2).

Results

Mean T2* values for the meniscal repair group demonstrated a wide range and no apparent trend. The mean and standard

Discussion

Previous studies have demonstrated wide variation in the accuracy of conventional MRI in assessing meniscal healing

Table 2 Fast spin echo MRI grading system

Criterion	Point-based grading system
Extrusion	None=0; <1/3=1; 1/3–2/3=2; >2/3=3
Signal of surgically repaired meniscal horn(s)	Normal fibrocartilage=0; increased signal in <1/3 of meniscal horn=1; increased signal in >1/3 of meniscus=2; diffusely increased intrameniscal signal=3
Presence of tear in non-operated portion of meniscus	Normal=0; tear=1; displaced tear=3
Degree of healing	Healed (no fluid imbibition)=0; fluid imbibition extending to a single articular surface=1; fluid imbibition extending to both articular surfaces=2
Synovitis	Normal=0; <33% maximal potential distention=1; 33–66% maximal potential distention=2; >66% maximal potential distention=3

Table 3 Postoperative UTE T2* values of repair group

Patient no.	Posterior horn T2* mean±SD (ms)		Anterior horn mean T2* mean±SD (ms)	
	6 months	12 months	6 months	12 months
1	10.6±12.6	3.7±1.5	4.0±1.8	3.4±1.1
2	8.3±13.1	4±1.8	7.2±3	7.4±3.4
3	3.7±1.2	4.4±3	4.5±1.7	2.5±1.0
4	5.1±2.9	4.8±2.1	3.6±1.3	5.8±3.2
Mean	6.9±7.5	3.0±2.1	4.8±2.0	4.8±2.2

following repair. One study evaluated symptomatic and asymptomatic patients with MRI and conventional, double-contrast arthrography at 8 months following meniscal repair [7]. The results demonstrated excellent MRI correlation with arthrography in assessing meniscal repair. In addition, MRI proved more accurate than arthrography in discriminating partial healing from non-healing of the repair in eight cases that had second-look arthroscopy because of persistent or recurrent symptoms. Muellner et al. evaluated 23 open meniscal repairs in 22 patients with a mean follow-up of 12.9 years using patient history and clinical examination and

in 19 cases using MRI [4]. The study concluded that MRI played a limited role in evaluating healing following meniscal repair; however, the accuracy of MRI findings was only compared to clinical assessment. A subsequent study with 81 patients (89 menisci) comparing MRI with second-look arthroscopy demonstrated an accuracy range of 85–91% for fluid-sensitive MR sequences in evaluating meniscal healing following repair [3]. Direct and indirect magnetic resonance arthrography (MRA) has also been used to improve diagnostic accuracy, but researchers have demonstrated similar results compared to conventional MRI with accuracies ranging between 80 and 85% for all three techniques [9].

Prior research has demonstrated that UTE-T2* mapping is a clinically feasible and reproducible technique to evaluate the native, non-operated meniscus, both in vitro and in vivo [11]. The purpose of this pilot study was to generate preliminary, baseline data using an experimental UTE pulse sequence in patients who had undergone surgical manipulation of their menisci. The study illustrated a wide range of mean T2* values for both the repair and meniscectomy groups. Although the T2* values changed over time, the values did not reveal a trend in either the repair or meniscectomy

Fig. 1. Maturation of T2* values following meniscal repair. Sagittal STIR and FSE PD pulse sequences of patient 1 demonstrate faint, intermediate signal intensity within the posterior horn (arrows), without fluid imbibition to suggest delayed healing or re-tear, unchanged between the 6- (a, b) and 12- (d, e) month intervals following meniscal repair. Sagittal UTE images adjacent to the corresponding FSE images, with regions of interest drawn around both the anterior and posterior horns, demonstrate interval maturation with shorter and more homogeneous T2* values at 12 months (f) compared to 6 months (c).

Table 4 Postoperative UTE T2* values of partial meniscectomy group

Patient no.	Posterior horn T2* mean±SD (ms)		Anterior horn mean T2* mean±SD (ms)	
	6 months	12 months	6 months	12 months
5	3.7±1.3	3.4±1.6	6.1±3	3.8±2.2
6	5.1±2.7	4.4±5.5	4.8±2.1	3.8±6.1
7	2.9±1.1	2.6±1	3.3±1.4	3.0±0.9
8	3.2±1	6.8±4.2	3.2±1.0	5.7±1.8
Mean	3.7±1.5	4.3±3.1	4.4±1.9	4.1±2.8

group. In three of the four patients who underwent repair, T2* values of the repaired meniscus increased. This increase was seen in the repaired anterior horn of patient 2's bucket handle tear and repaired posterior horn of patient 3 as well as within the non-repaired, ipsilateral anterior horn of patient 4. In one of the four patients who underwent partial meniscectomy (patient 8), increased T2* values were seen in both the operated posterior horn and non-operated ipsilateral anterior horn.

The study population was diverse, and many factors may have affected quantitative assessment. Changes in T2* values may reflect the degree of healing of a repaired meniscus, tissue vascularity, the degree of preexisting

degeneration of the fibrocartilage matrix, concomitant articular cartilage degeneration, the degree of synovial inflammation in the joint, and tissue augmentation with growth factors. Mechanical loading also likely has an important effect on T2* values and will be affected by the rehabilitation protocol following surgery and a patient's current level of activity at the time of qMRI evaluation.

Using an ovine meniscal model, our study group previously demonstrated that T2* mapping was sensitive to temporal and zonal differences of meniscal repair and that multiphoton microscopy and T2* values reflected alterations in meniscal integrity following surgical manipulation [2]. Williams et al. documented higher T2* mean values in the region of a histologically confirmed tear, in vitro human meniscal specimens, as well as higher T2* mean values in vivo ACL-injured subjects with concomitant medial meniscal tear compared to ACL-injured subjects without clinical evidence of meniscal pathology [11].

As mentioned previously, our hypothesis was that higher T2* values would correlate with increased meniscal signal on routine FSE images and that the inverse would also hold true. A direct correlation between the FSE and UTE data, however, was not appreciated in this study, and in fact, for patient 8, an inverse correlation was identified. This patient demonstrated delayed healing or re-tear at the site of his

Fig. 2. Partial meniscectomy. Sagittal STIR and FSE PD pulse sequences of patient 8 demonstrate fluid signal intensity within the site of partial meniscectomy extending to both articular surfaces (*thick arrows*), indicating delayed healing or re-tear, within the posterior horn at the 6-month interval (**a**, **b**). The corresponding sagittal UTE map (**c**) with regions of interest drawn around the anterior and posterior horn is also shown. At 12 months following surgery, intermediate signal intensity within the posterior horn is now seen (*thick arrows*) (**d**, **e**), indicating interval healing but with an increase in mean T2* values, possibly due to increasing load in the face of partial debridement (**f**). Also note moderate synovitis at 6 months (*thin arrow*, **a**) which has resolved by 12 months (**b**).

partially resected posterior horn at the 6-month interval but complete healing at the 12-month interval, as determined by conventional FSE images (Fig. 2). Mean T2* values of both the operated posterior and non-operated anterior horns, however, increased from 3.2 to 6.8 and 3.2 to 5.7 ms, respectively, between 6 and 12 months. Although there is no histopathologic corroboration, we speculate that the UTE sequence may reflect gradually increased load in the face of partial debridement between the 6- and 12-month intervals for patient 8's meniscus that is otherwise undetected with routine FSE sequencing.

While acknowledging the data are preliminary and likely reflect insufficient study power given a pilot cohort of eight patients, we speculate that the T2* mapping sequence reflects the microscopic structure of the postoperative meniscus and thus provides insight into the biomechanical function of the tissue. Conventional FSE images may demonstrate apparent tissue "healing," but we really do not know if such healed tissue functions as a normal meniscus. The UTE sequence likely provides a more accurate evaluation of the tissue's organization and function. In all subjects' anterior and posterior horns, regardless of whether surgical manipulation was performed in that horn, T2* differences were detected, despite employing the identical MR scan parameters on the same magnet. The data may reflect changes in loading of the meniscus, with redistribution of load to the non-operated meniscal horn, as the ovine model of meniscal repair had previously shown [2]. Further studies are required to understand the relationship between the T2* values, meniscus microstructure, and ultimate meniscus function.

Surgical techniques and materials, including the use of biological augmentation materials, may contribute to the variability in T2* measurements by altering tissue properties, independent of the natural healing response. The longest T2* values were measured in patients 1 and 2 who underwent augmentation of their repair with PRFM. These same patients also demonstrated the greatest decline in these values between 6 and 12 months. This may reflect an initial upregulation of inflammatory mediators at the site of the fibrin matrix with subsequently decreased inflammatory response over time. The number and type of sutures, not uniformly documented in the surgical reports of the study patients, may also contribute to the degree of inflammation at the surgical site.

Surgical technique and materials are only two of many variables that need to be considered during planning of future, longitudinal studies. Additional variables, not controlled for in this study but which can be readily identified and controlled for in future trials, include (1) tear morphology, i.e., vertical (bucket handle, radial) versus horizontal, (2) tear location, whether in a vascular or relatively avascular zone, which could predict the probability of healing, (3) type of surgery performed, i.e., repair vs. partial meniscectomy, and (4) the surgeon performing the operation. As alluded to previously, the patients may have participated in different physical therapy regimens and returned to different levels of exercise and at different times postoperatively, possibly affecting healing of their menisci. With an adequately powered trial, it may be possible to detect which variables have the greatest impact on T2* values.

In conclusion, this study presents preliminary observational data to be used as a baseline for future studies and demonstrates that a wide range of T2* values may be detected in postoperative menisci. Larger, more controlled studies will have to be performed to more accurately detect trends in T2* values and the degree of meniscal healing, in conjunction with conventional FSE MRI, second-look arthroscopy, and patient symptomatology. The ultimate goal is to detect meniscal healing or pathology more reliably and at an earlier interval compared to currently available, more invasive methods.

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Disclosures

Conflict of Interest: Darryl B. Sneag, MD, reports institutional research funding from General Electric Healthcare during the conduct of the study. Matthew F. Koff, PhD, reports grant funding from NIH/NIAMS, outside the work. Scott A. Rodeo, MD, is a paid consultant for Smith and Nephew and has stocks/stock options from Cayenne Medical. Hollis G. Potter, MD, reports institutional funding from General Electric Healthcare during the conduct of study and grant funding from NIH/NIAMS, outside the work.

Human/Animal Rights: All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008 (5).

Informed Consent: Informed consent was obtained from all patients for being included in the study.

Required Author Forms Disclosure forms provided by the authors are available with the online version of this article.

References

1. Farley TE, Howell SM, Love KF, Wolfe RD, Neumann CH. Meniscal tears: MR and arthrographic findings after arthroscopic repair. *Radiology*. 1991; 180: 517–522.
2. Koff MF et al. Correlation of meniscal T2* with multiphoton microscopy, and change of articular cartilage T2 in an ovine model of meniscal repair. *Osteoarthritis Cartilage*. 2013; 21: 1083–1091.
3. Miao Y, Yu JK, Ao FJ, et al. Diagnostic values of 3 methods for evaluating meniscal healing status after meniscal repair: comparison among second-look arthroscopy, clinical assessment, and magnetic resonance imaging. *Am J Sports Med*. 2011; 39(4): 735–742.
4. Muellner T, Egkher A, Nikilic A, Furnovics M, Metz V. Open meniscal repair: clinical and magnetic resonance imaging findings after twelve years. *Am J Sports Med*. 1999; 27: 16–20.
5. Pujol N, Panarella L, Selmi TA, Neyret P, Fithian D, Beaufils P. Meniscal healing after meniscal repair: a CT arthrography assessment. *Am J Sports Med*. 2008; 36: 1489–1495.
6. Rodeo SA. Meniscal Allografts—where do we stand? *AJSM*. 2001; 29: 246–261.
7. van Trommel MF, Potter HG, Ernberg LA, Simonian PT, Wickiewicz TL. The use of noncontrast magnetic resonance imaging in evaluating meniscal repair: comparison with conventional arthrography. *Arthroscopy*. 1998; 14: 2–8.

8. van Trommel MF, Simonian PT, Potter HG, Wickiewicz TL. Different regional healing rates with the outside-in-technique for meniscal repair. *Am J Sports Med.* 1998; 26: 446-452.
9. White LM, Schweitzer ME, Weishaupt D, et al. Diagnosis of recurrent meniscal tears: prospective evaluation of conventional MR imaging, indirect MR arthrography, and direct MR arthrography. *Radiology.* 2002; 222: 421-429.
10. Williams A, Qian Y, Bear D, Chu CR. Assessing degeneration of human articular cartilage with ultra-short echo time (UTE) T2* mapping. *Osteoarthritis Cartilage.* 2010; 18: 539-546.
11. Williams A, Qian Y, Golla S, Chu CR. UTE-T2* mapping detects sub-clinical meniscus injury after anterior cruciate ligament tear. *Osteoarthritis Cartilage.* 2012; 20: 486-494.